

Physics-based nonlinear noise modelling

Original

Physics-based nonlinear noise modelling / Bonani, Fabrizio; DONATI GUERRIERI, Simona; Ghione, Giovanni. - (2009).
(Intervento presentato al convegno European Microwave Week tenutosi a Roma, Italy nel 28 September - 2 October).

Availability:

This version is available at: 11583/2281567 since:

Publisher:

Published

DOI:

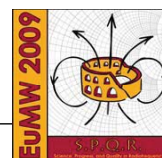
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Nonlinear Noise Modelling and Large-Signal Low-Noise Microwave Circuit Design

Organisers:

Matthias Rudolph, Ferdinand-Braun Institut (FBH), Berlin, Germany
Fabio Filicori, University of Bologna, Italy

Abstract:

This workshop is focussed on recent developments in the field of nonlinear noise models and design techniques for low-noise microwave circuits which are intrinsically subject to large-signal operating conditions. In fact, many of the fundamental building blocks for the development of high-performance communication systems, like low-phase-noise oscillators, mixers or interference-robust low-noise amplifiers, are subject to important noise generation phenomena which are strongly conditioned by the presence of large-amplitude signals. In such cases, normally characterized by periodic or almost periodic non-linear operation, noise modelling in electron devices becomes much more complex, in comparison with the linear steady-state case, since cyclostationary, instead of conventional, stationary equivalent noise sources must be considered in the device models or low noise circuit design.

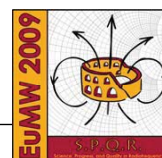
In this workshop, after outlining the basics of noise generation in semiconductors and of numerical physics-based noise models, non linear, compact HBT and FET non-linear noise models will be described with examples of application to noise analysis in non linear microwave circuits. Design approaches for low-noise oscillators, mixers and amplifiers will also be presented and discussed.

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Programme



8:45 - 9:20

Physics-Based Nonlinear Noise Modelling
Fabrizio Bonani, S. Donati Guerrieri, G. Ghione,
Politecnico di Torino, Italy

9:20 - 9:55

Non-Linear HBT Noise Modelling
and Applications
Christophe Nallatamby¹, E. Dupouy¹, J. Portilla²,
M. Prigent¹, J. Obregon¹,
¹ *University of Limoges, France*
² *University of the Basque country, Bilbao, Spain*

9:55 - 10:30

Non-Linear FET Noise Modelling
and Applications
C.Florian, P.A.Traverso, F. Filicori, Univ. Bologna, Italy

10:30 - 11:00

Coffee Break

11:00 - 11:35

Low Phase-Noise Oscillator Design Techniques,
Applications and Future Trends
U. L. Rohde, Univ. Cottbus, Germany
Ajay K. Poddar, Synergy Microwave Corp., NJ, USA

11:35 - 12:10

Noise in Mixers
Steven Maas, AWR, USA

12:10 - 12:45

Highly Linear Low-noise Amplifiers
Matthias Rudolph, Ferdinand-Braun-Inst. (FBH), Germany

12:45 - 14:00

Lunch

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Physics-Based Nonlinear Noise Modelling

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Outline

- Motivation
- Overview on numerical noise modelling
 - Small-signal (stationary)
 - *Forced* large-signal (cyclostationary)
 - *Autonomous* large signal
- Modeling low frequency noise
- Evaluating the Large Signal working point
- Case studies
- Conclusions

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- Low-noise circuits important in RF & microwave telecommunication systems
 - **Linear** circuits (e.g., low noise amplifiers)
 - **“Nonlinear”** circuits (e.g., mixers, frequency multipliers, oscillators)
- Physics-based (PB) simulation is a powerful tool for:
 - TCAD Device design and optimization
 - Development of compact, circuit-oriented model with sound physical basis
 - Understanding exotic noise mechanisms (1/f?)

A few basics on physics-based noise modelling - I

- Microscopic (carrier **velocity or population**) fluctuations are a *small perturbation* of
 - **DC steady-state** → *Small-signal, stationary noise*
 - **Large-signal (quasi) - periodic steady state** → *LS (quasi)-cyclostationary noise*
 - **LS steady-state of autonomous system** → *LS (oscillator) stationary (?) noise*

- Terminal (v,i) fluctuations are evaluated through a (linear) **Green's function approach** from (spatially uncorrelated) microscopic (charge or current density) fluctuations distributed in the device volume
 - **SS conditions** → Superposition + *Filtering of microscopic noise source spectra*
 - **LS conditions** → Superposition + *Filtering & frequency conversion*

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- The **Green's function** (→ “impedance field”) can be derived through SS (small-signal) or SSLS (ss with respect to LS) linearization from **any PDE based physical model**:
 - Drift-diffusion (DD)
 - Energy balance
 - Full hydrodynamic, N moments from BE

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1. Evaluate the **noiseless working point**

- Noise sources are **switched off**
- Solution is $(\varphi_0, n_0, p_0, n_{t,k0})$
- The working point depends on the **applied generators** → **might depend on time and require mixed-mode simulation** → CPU-intensive for the large-signal case

2. Add (model) the **microscopic noise sources**

- The working point is perturbed by **fluctuations** $\delta\alpha$

3. Solve the (linear) perturbed system to evaluate the **terminal electrical fluctuations** (noise generators) through the Green's function approach

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Example: DD model, SS noise

$$\varepsilon \nabla^2 \Psi = -\rho(n, p, \Psi)$$

$$\frac{\partial n}{\partial t} = -\frac{1}{q} \nabla \cdot \vec{J}_n - U_n$$

$$\frac{\partial p}{\partial t} = +\frac{1}{q} \nabla \cdot \vec{J}_p - U_p$$

Linearization
around DC
steady state,
frequency
domain &
**Langevin
sources**

**Scalar & vector
Green's functions**

$$\begin{cases} G_\alpha(\vec{r}, \vec{r}_1) \\ \nabla_{\vec{r}_1} G_\alpha(\vec{r}, \vec{r}_1) \end{cases}$$

$$\alpha = n, p$$

$$\varepsilon \nabla^2 G_\alpha = -\Lambda_\Psi(\tilde{n}, \tilde{p}, G_\alpha)$$

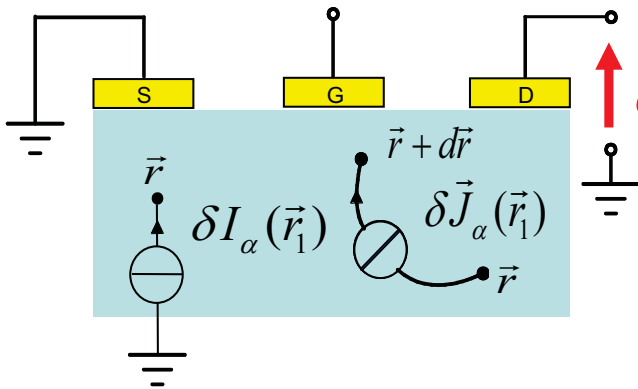
$$j\omega \tilde{n} = -\Lambda_n(\tilde{n}, \tilde{p}, G_\alpha) + \delta_{\alpha,n} \delta(\vec{r} - \vec{r}_1)$$

$$j\omega \tilde{p} = -\Lambda_p(\tilde{n}, \tilde{p}, G_\alpha) + \delta_{\alpha,p} \delta(\vec{r} - \vec{r}_1)$$

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$$\delta V_{D,\alpha} = G_{\alpha}(\vec{r}_D, \vec{r}_1) \delta I_{\alpha}(\vec{r}_1) + \nabla_{r_1} G_{\alpha}(\vec{r}_D, \vec{r}_1) \cdot \delta \vec{J}_{\alpha}(\vec{r}_1)$$

$\delta I_{\alpha}(\vec{r}_1) \rightarrow$ e/h **GR noise source**
(population fluctuations)

$\delta \vec{J}_{\alpha}(\vec{r}_1) \rightarrow$ e/h **diffusion noise source**
(velocity fluctuations)

- Correlation matrix of open-circuit voltage noise fluctuations:

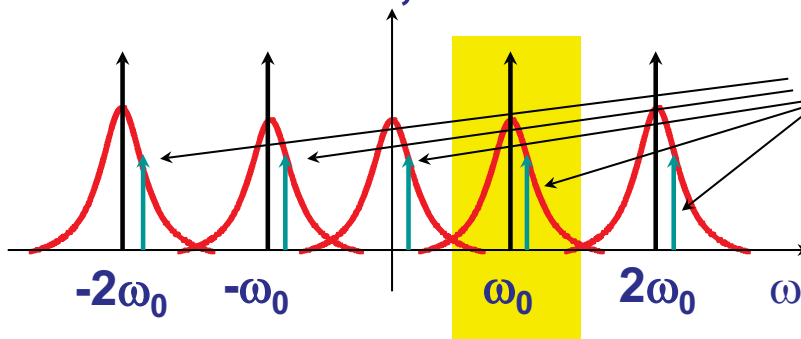
$$S_{\delta V_i \delta V_j}(\omega) = \sum_{\alpha=n,p} \int_{\Omega} \vec{G}_{\alpha}(\vec{r}_i, \vec{r}, \omega) \cdot \mathbf{K}_{\delta \vec{J}_{\alpha} \delta \vec{J}_{\alpha}}(\vec{r}, \omega) \cdot \vec{G}_{\alpha}^*(\vec{r}_j, \vec{r}, \omega) d\vec{r} + \sum_{\alpha,\beta=n,p} \int_{\Omega} G_{\alpha}(\vec{r}_i, \vec{r}, \omega) K_{\gamma_{\alpha} \gamma_{\beta}}(\vec{r}, \omega) G_{\beta}^*(\vec{r}_j, \vec{r}, \omega) d\vec{r}$$

$\mathbf{K}_{\delta \vec{J}_{\alpha} \delta \vec{J}_{\alpha}} = 4q^2 \alpha \mathbf{D}_{\alpha} \rightarrow$ e/h **diffusion local noise source**

$K_{\gamma_{\alpha} \gamma_{\beta}}(\vec{r}, \omega) \rightarrow$ e/h **GR local noise source**

- Analog applications often require **periodic** or **quasi-periodic** LS operation
- In LS operation microscopic noise sources are **amplitude modulated** by the periodic LS steady-state leading to → **cyclostationary microscopic sources with correlated frequency components**
- Those are described by the **Sideband Correlation Matrix (SCM)** formalism

- Only the spectral components in each **sideband** having the **same distance** from the LS harmonics, are **correlated**



Correlated sidebands
of noise process y

$$\omega_k = k\omega_0$$

LS harmonics

$$\omega_k^+ = \omega_k + \omega$$

sidebands

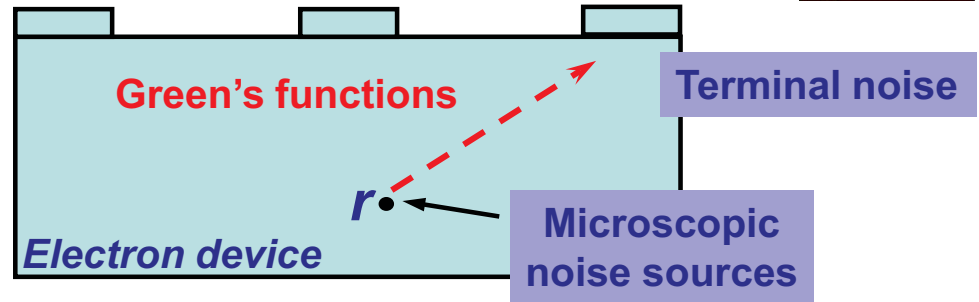
- 2nd order statistical properties through the **sideband correlation matrix (SCM)**:

$$\left(\mathbf{S}_{y,y}(\omega) \right)_{k,l} = \left\langle \tilde{y}(\omega_k^+) \tilde{y}^*(\omega_l^+) \right\rangle$$

ω is called
**sideband
frequency**

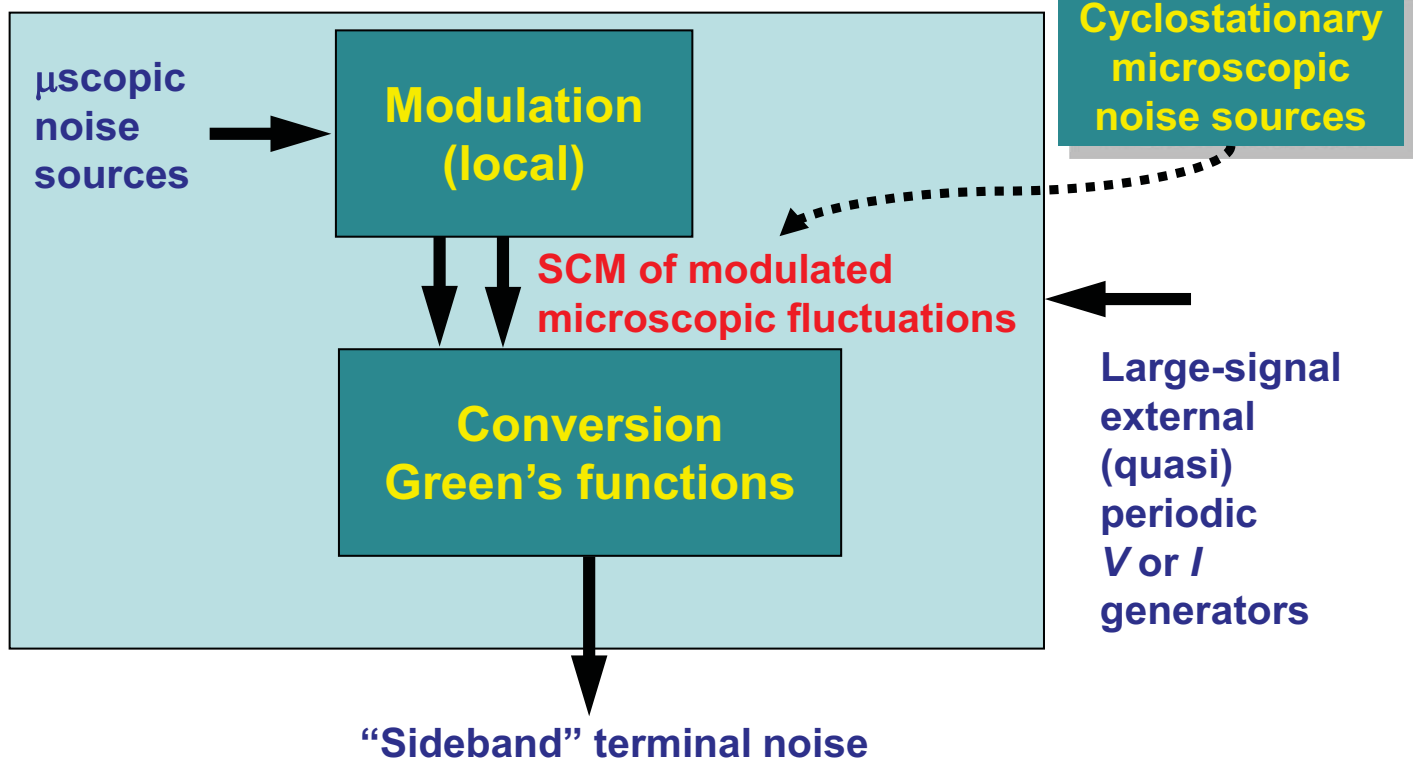
LS cyclostationary noise - II

LS extension of
Green's function
approach



- Green's functions → **conversion** Green's functions, implying noise frequency conversion into LS spectrum sidebands
- After **propagation** & **conversion** noise around each harmonic is due to
 - microscopic noise source **at that sideband**
 - source conversion **from other sidebands**

LS cyclostationary noise - III



- **Oscillator noise** → open research issue and object of debate even at circuit and system level
- A. Demir's approach (system level) accounting both for **coloured** and **white noise sources** → viable way for extension to device level
- Work by group of Seoul National University (white diffusion noise sources)

- Through standard (e.g. finite box – Scharfetter-Gummel) discretization the Green's function is derived from a **linear system** (← SS or SSLs)
- Efficient evaluation of the Green's functions at device terminals through **adjoint** and **generalized adjoint** techniques
- ☹ **Bottleneck**: LS (quasi) periodic solution through Harmonic Balance

- **Low-frequency** (coloured, **1/f** or **Lorentzian**) noise important in many analog applications (mixers, multipliers, oscillators...) where noise frequency conversion takes place
- Low-frequency noise → superposition of **bulk, surface or interface GR noise**
- **GR trap-assisted** noise → theory developed by van Vliet in 1960 → **trap level rate equations** added to DD model

Model + traps: bipolar drift-diffusion

- N_t **traps** included
- Device **mesh**: N_i internal nodes and N_x external nodes on metallic contacts
- Device **contacts**: N_c+1 , one grounded

$$\nabla^2 \varphi = -\frac{q}{\varepsilon} \left(p - n - \sum_{k=1}^{N_t} n_{t,k} \right)$$

$$\frac{\partial n}{\partial t} = -\nabla \cdot (n \mu_n \nabla \varphi - D_n \nabla n) - U_n + \gamma_n$$

$$\frac{\partial p}{\partial t} = +\nabla \cdot (p \mu_p \nabla \varphi + D_p \nabla p) - U_p + \gamma_p$$

$$\frac{\partial n_{t,k}}{\partial t} = -U_k + \gamma_k \quad k = 1, \dots, N_t$$

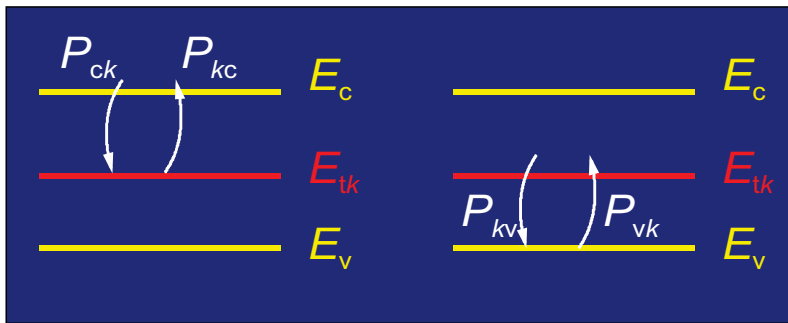
Trap level transition rates

- N_t (local) trap rate equations → SRH model
- **Noninteracting traps** considered;
superposition → **1/f spectrum**

total trap density $c = (\text{cross sect.}) \times v_{th}$

$$P_{ck} = c_{n,k} n (N_{t,k} - n_{t,k}), \quad P_{kc} = c_{n,k} n_{1,k} n_{t,k},$$

$$P_{vk} = c_{p,k} p_{1,k} (N_{t,k} - n_{t,k}), \quad P_{kv} = c_{p,k} p_{t,k} n_{t,k}$$



$$n_{1,k} = N_c \exp\left(\frac{E_{t,k} - E_c}{k_B T}\right)$$

$$p_{1,k} = N_v \exp\left(\frac{E_v - E_{t,k}}{k_B T}\right)$$

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SS - GR local noise source

$$K_{\gamma_n, \gamma_n} = 2(P_{ck0} + P_{kc0}),$$

$$K_{\gamma_p, \gamma_p} = 2(P_{vk0} + P_{kv0}),$$

$$K_{\gamma_n, \gamma_p} = 0,$$

$$K_{\gamma_k, \gamma_k} = 2(P_{ck0} + P_{kc0} + P_{vk0} + P_{kv0}),$$

$$K_{\gamma_n, \gamma_k} = -2(P_{ck0} + P_{kc0}),$$

$$K_{\gamma_p, \gamma_k} = 2(P_{vk0} + P_{kv0})$$

$\gamma_n \rightarrow$ Langevin source,
e-continuity equation

$\gamma_p \rightarrow$ Langevin source,
p-continuity equation

$\gamma_k \rightarrow$ Langevin source,
kth trap rate equation

$$P_{ck} = c_{n,k} n (N_{t,k} - n_{t,k}),$$

$$P_{kc} = c_{n,k} n_{1,k} n_{t,k},$$

$$P_{vk} = c_{p,k} p_{1,k} (N_{t,k} - n_{t,k}),$$

$$P_{kv} = c_{p,k} p n_{t,k}$$

Trap transition
probabilities



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- In LS conditions the white microscopic RG noise sources are **(quasi) periodically** modulated by the working point
- Noise source SCM, e.g.:

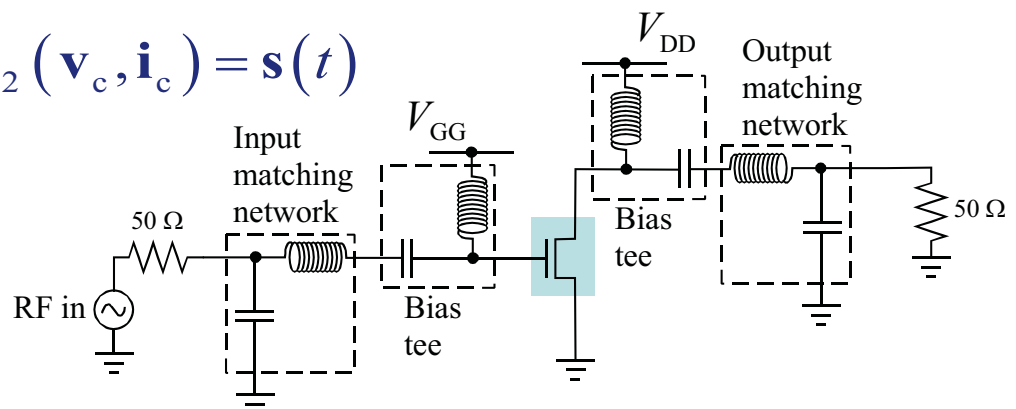
$$\left(\mathbf{K}_{\gamma_n, \gamma_n} \right)_{l,m} = 2 \left(P_{ck0, l-m} + P_{kc0, l-m} \right)$$

**(l-m)-th Fourier component
of transition rate**

Solving the PB model in LS: the embedding circuit

- Represented, in its simplest form, by a **memory relationship** between v_c , i_c and the applied generators $s(t)$
 - For **periodic excitation**, $s(t+T)=s(t)$
 - For **autonomous circuit**, $s(t)=0$

$$\frac{d}{dt} \mathbf{e}_1(v_c, i_c) + \mathbf{e}_2(v_c, i_c) = s(t)$$



- (Space) discretized PB model + embedding circuit → **differential algebraic equation (DAE)**

System size:
$$N_{eq} = (3 + N_t)(N_i + N_x) + 2N_c$$

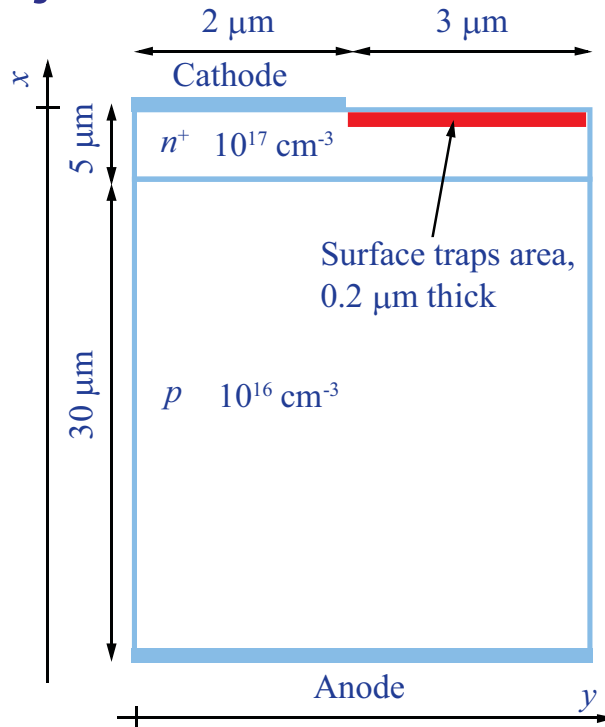
For a **3-terminal** device with **2000** mesh nodes
and **3** traps $N_{eq}=12,004!$

- Direct computation of the steady-state response
 - Frequency-domain: **Harmonic Balance (HB)**
 - Time-domain: **shooting method**
 - Autonomous case?

- **2D n^+p diode**
 - motivation: low-frequency noise compact modelling usually based on **amplitude modulation of stationary SS noise generators** → is this generally correct / accurate?
- **GaAs MESFET and AlGaAs/GaAs HEMT Mixer**
 - 2D LS mixed-mode noise simulation

2D n^+p diode

- n^+p junction diode → 1 **bulk** and 3 **surface** traps



Bulk trap:

$$N_t = 5 \times 10^{12} \text{ cm}^{-3}$$

$$c_n = c_p = 5.7 \times 10^{-13} \text{ cm}^3/\text{s}$$

energy level: 0.56 eV below E_c

Surface traps:

$$N_t = 1.67 \times 10^{16} \text{ cm}^{-3}$$

$$N_{t,\text{surf}} = 3.34 \times 10^{11} \text{ cm}^{-2}$$

energy level: 0.26 eV below E_c

$$\text{Trap 1: } c_n = c_p = 5.7 \times 10^{-14} \text{ cm}^3/\text{s}$$

$$\text{Trap 2: } c_n = c_p = 5.7 \times 10^{-15} \text{ cm}^3/\text{s}$$

$$\text{Trap 3: } c_n = c_p = 5.7 \times 10^{-16} \text{ cm}^3/\text{s}$$

Large-signal simulation:

6 harmonics + DC

working point: 0.6 V DC

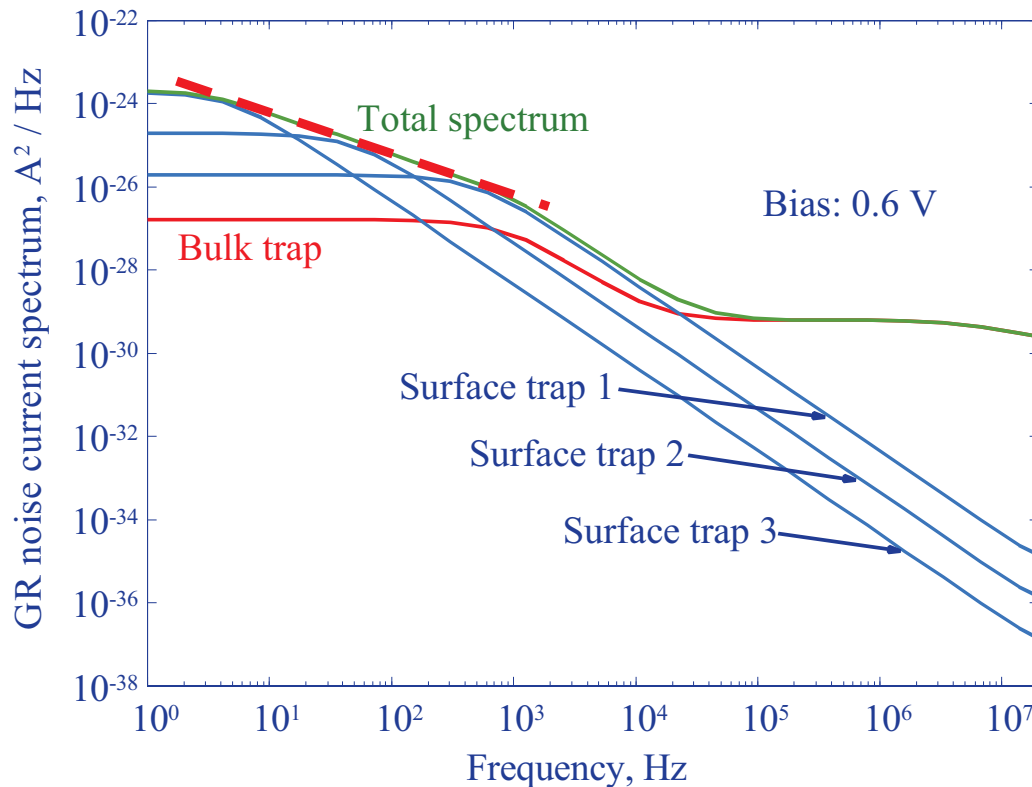
+ 50 mV tone @ 5 MHz

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Stationary GR noise spectrum

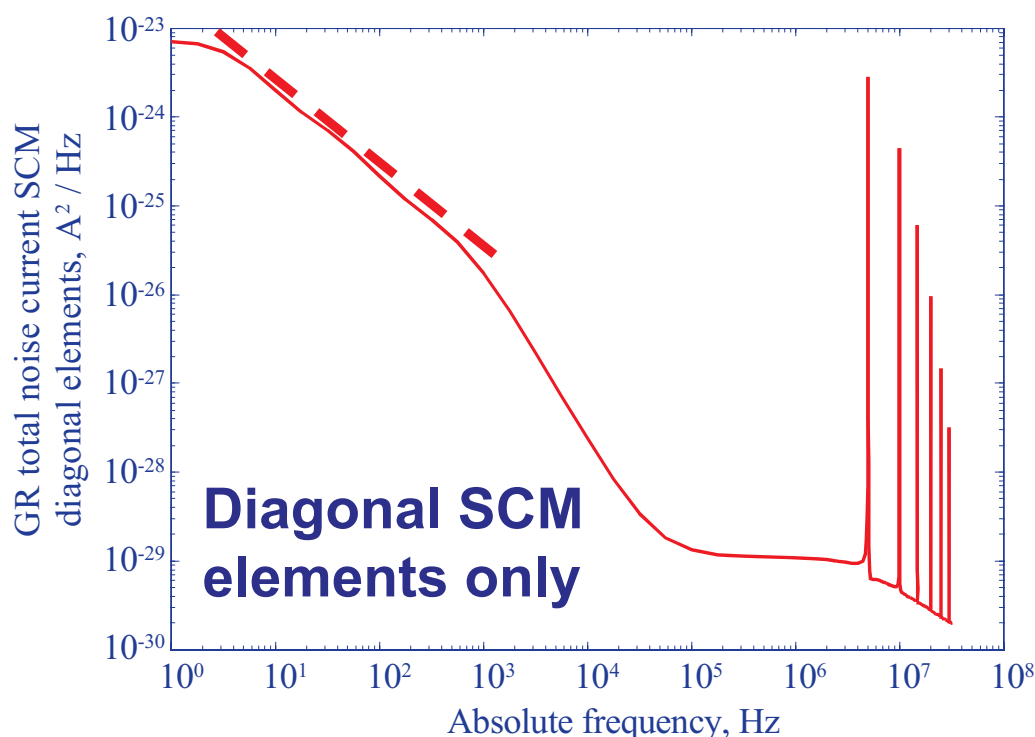


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Cyclostationary GR noise spectrum (absolute freq.)

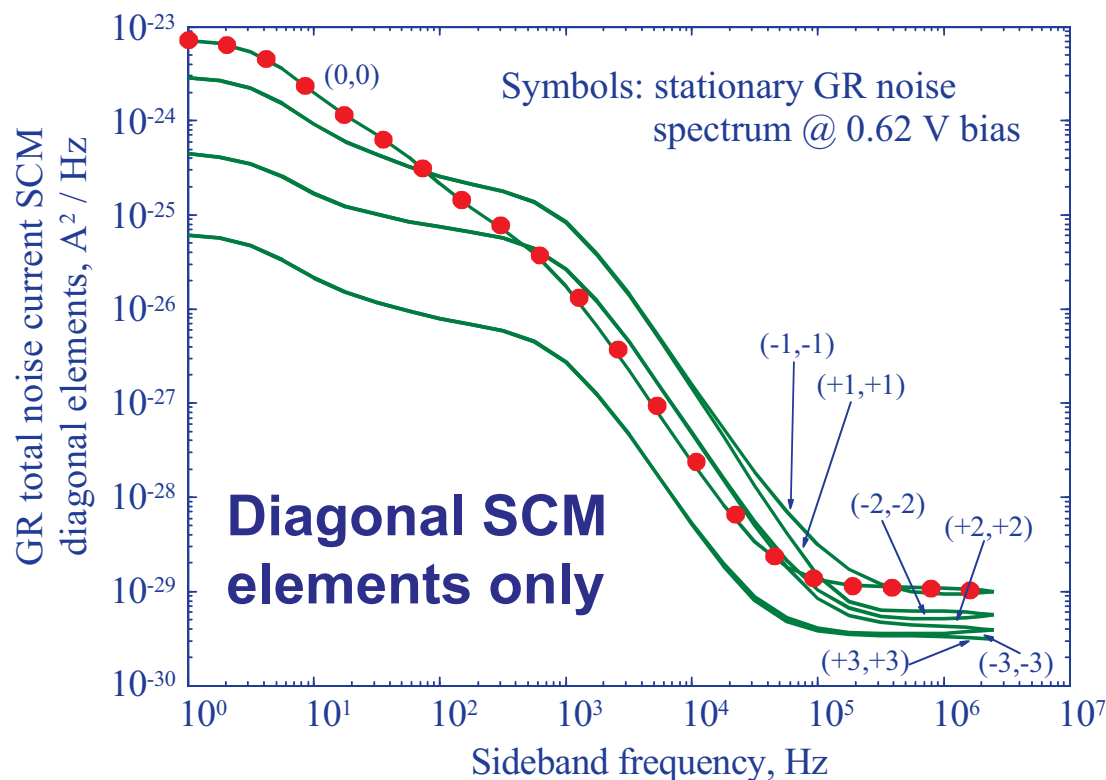


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Cyclostationary GR noise spectrum (sideband freq.)



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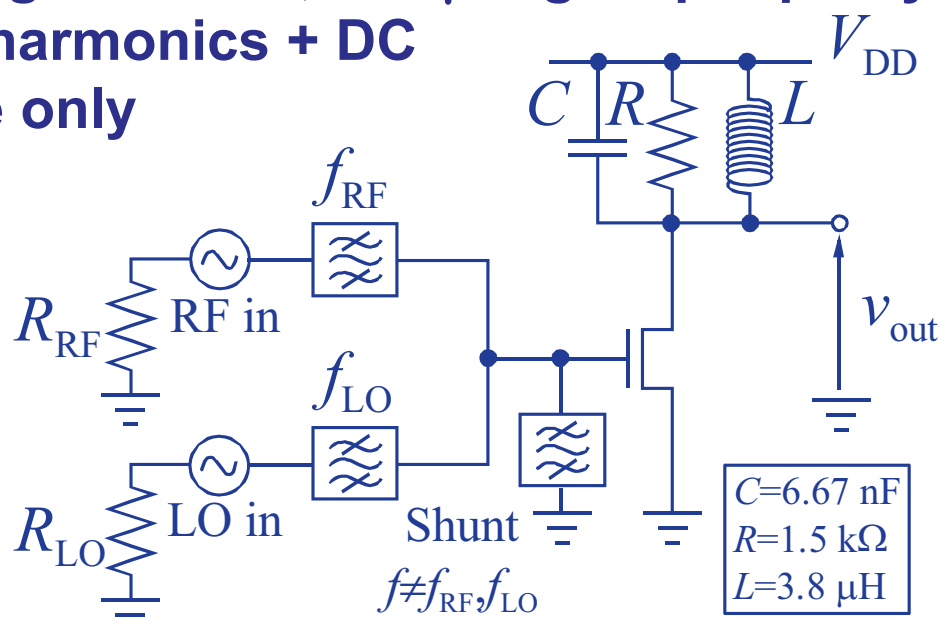
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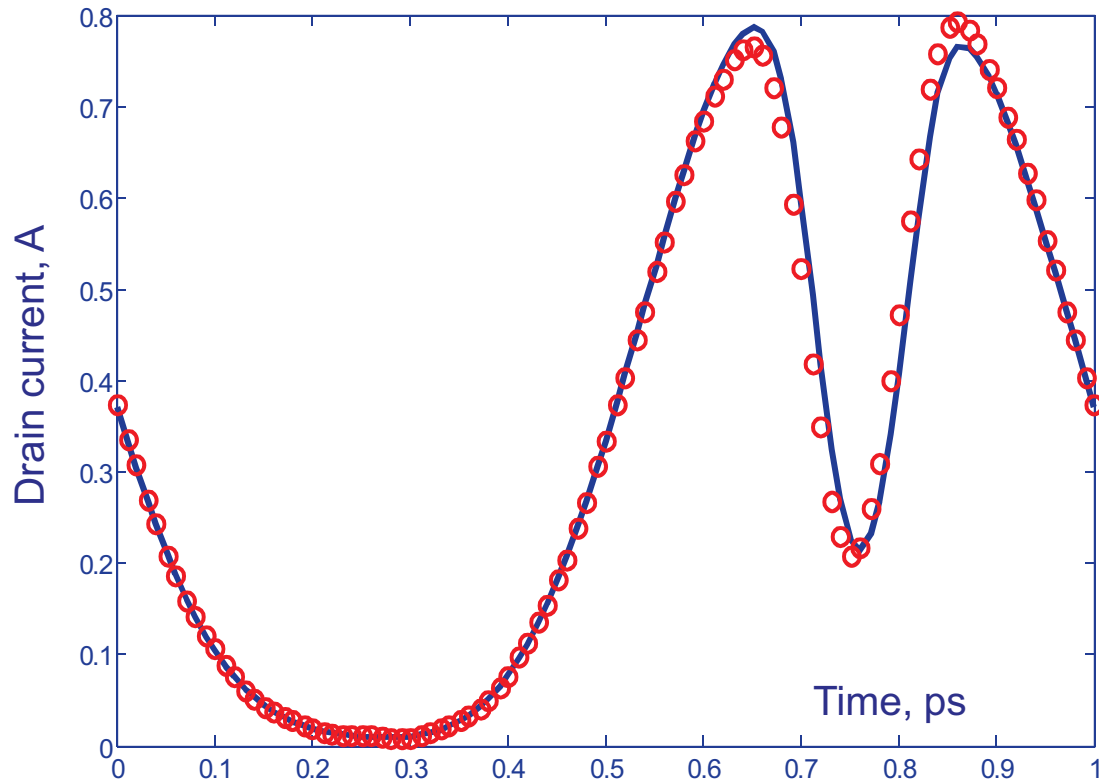
- The SS 1/f like behaviour is **preserved in the (0,0) sideband**
- However, **conversion to upper sidebands acts differently for bulk and surface traps**
- Therefore, noise in upper sidebands is **markedly different from modulated SS noise**
→ which would have the same 1/f like behaviour for all sidebands
- Impact on **compact modelling!**

Mixer circuit

- Downconversion mixer, $f_{LO}=1$ GHz, $f_{RF}=1.001$ GHz
- Device: 0.3 μm gate HEMT, 100 μm gate periphery
- 1300 nodes, 4 harmonics + DC
- Diffusion noise only
- Noiseless LO



Mixer working point

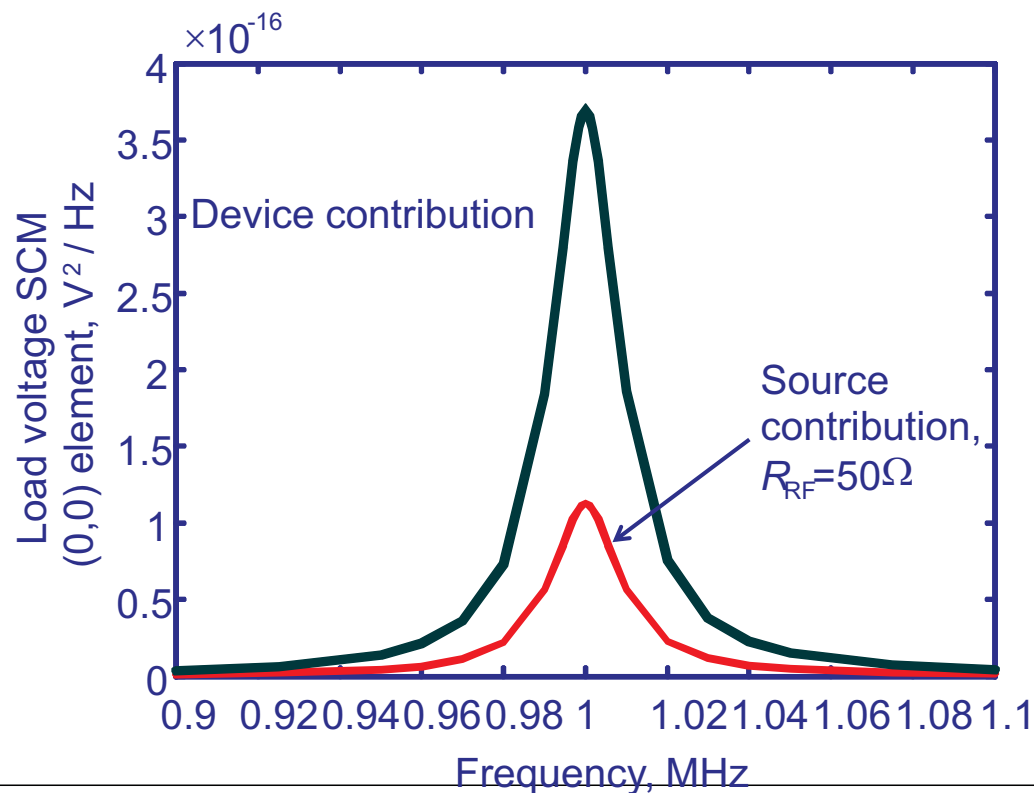


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Load noise voltage around IF

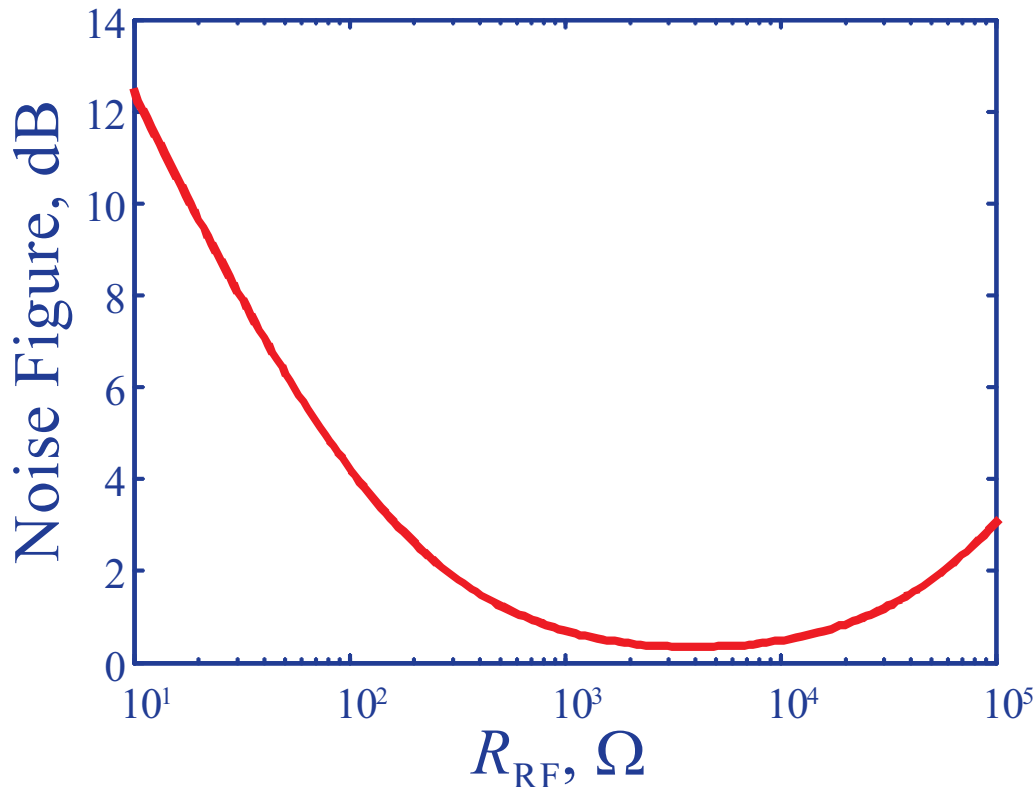


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Intrinsic noise figure vs. RF source resistance



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Conclusions

- Numerical noise simulation has (hopefully) reached maturity
- Progress made in understanding **low-frequency noise** ($\rightarrow 1/f$) and its **frequency conversion** (also \rightarrow compact modelling)
- Encouraging advances in **oscillator** PB modelling
- LS noise simulation requires more efficient WP solvers (time domain?)
- General strategy for LS compact modelling still an open problem – but this is another story!

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